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REVIEW OF OBSERVATIONS FROM HYDROSTATIC PRESSURE MEASURING DEVICES, WAPPAPELLO DAM, WAPPAPELLO, MISSOURI

W. C. Sherman, et al

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

June 1957

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REVIEW OF OBSERVATIONS FROM HYDROSTATIC PRESSURE MEASURING DEVICES WAPPAPELLO DAM, WAPPAPELLO, MISSOURI

TECHNICAL REPORT NO. 3-460

June 1957

Prepared for

The President, Mississippi River Commission

by

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

ARMY MRC VICKSBURG MISS

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PREFACE

The study reported herein is one of a number of similar studies of foundation and soil mechanics features of completed structures in the Lower Mississippi Valley Division*. These studies are being made for the Engineering Division, Mississippi River Commission, by the Waterways Experiment Station.

Wappapello Dam was designed by and built under the supervision of the Memphis District, CE. Construction was begun in September 1938 and completed in May 1941. Observations of piezometers and hydrostatic pressure cells were made during construction and have been continued to date. Measurements of seepage emerging from the toe drainage system for the dam were made in 1941, 1942, and 1945.

This report contains analyses of seepage and hydrostatic pressure data obtained since 1941 and an evaluation of the safety of the foundation downstream of the dam with respect to uplift. Although seepage and substratum pressures do not appear to be critical, some of the piezometers in the embankment and foundation will continue to be observed as a check on hydrostatic pressures and the effectiveness of the drainage system.

Analyses of data in this report were made by Mr. W. M. Nichols and Mrs. Marie M. Lassiter, both formerly with the Soils Division, Waterways Experiment Station, and Mr. W. C. Sherman, under the direction of Messrs. W. J. Turnbull, W. G. Shockley, and R. I. Kaufman, Soils Division, Waterways Experiment Station. This report was prepared by Messrs. Sherman and Nichols.

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* A list of associated reports is given on the inside of the front cover of this report.

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SUMMARY

Wappapello Dam is a flood control dam located in southeast Missouri on the St. Francis river. The embankment is of rolled fill construction and is about 70 ft high and 2700 ft long. To the left of the old river channel the foundation consists of a rather impervious silt stratum 50 ft thick underlain by 55 to 85 ft of alternating strata of clay and sand with some gravel extending to bedrock. To the right of the old river channel the top stratum consists of a thin layer of silt having a maximum thickness of 4 ft underlain generally by silty sand and deeper strata of sands and gravel with clay pockets extending to bedrock. The embankment is provided with a rock toe drain extending the length of the dam.

Hydrostatic pressure measurement devices, consisting of piezometers and pressure cells, were installed to measure the hydrostatic pressure in the foundation beneath the channel fill and in the foundation along the downstream toe of the embankment south of the channel fill. Piezometers were installed to determine the pattern of seepage through and beneath the embankment at sta 15+05B. Hydrostatic pressure cells also were installed in some of the clayey strata underlying the dam to measure the state of consolidation during and after construction. Sixty-nine pressure cells of three different types were installed but only 9 of the cells were still operating in January 1956. The majority of the operative pressure cells are located in the clayey strata beneath the dam near sta 9+00D; data from the devices at this location are not particularly pertinent to the problem of underseepage but are included in this report. Seepage measurements were made during periods of high reservoir stages in the winter of 1941-1942 and in March 1945.

The reservoir stage reached an elevation of 399.3 in April 1945 or 4.3 ft above the crest of the spillway. This stage resulted in a net head on the dam of about 85 per cent of that expected with the reservoir at the flood crest (el 410.4). As no sand boils or piping

occurred in 1945 as a result of seepage or uplift, it is considered that the dam will be safe with respect to piping and uplift with the reservoir pool at the flood crest.

Analysis of the data from the piezometers and pressure cells indicates that the toe drain is effective in reducing excess hydrostatic pressures in the upper pervious foundation strata and in providing an outlet for the controlled emergence of seepage, and the hydrostatic head in the deeper sand strata is not excessive for the existing overburden. The data also indicate that the seepage through the embankment and foundation is not significant. However, it is planned to continue observation of piezometers and seepage from the toe drainage system to check on the future performance of the toe drain.

REVIEW OF OBSERVATIONS FROM HYDROSTATIC PRESSURE MEASURING DEVICES WAPPAPELLO DAM, WAPPAPELLO, MISSOURI

PART I: INTRODUCTION

Purpose of Study

1. The purpose of this report is to evaluate the safety of Wappapello Dam with respect to piping and uplift at the downstream toe and to evaluate the significance of seepage through the embankment and foundation.

Scope of Report

2. This report presents an analysis of seepage through and hydrostatic pressures in the foundation and embankment measured since completion of the dam in 1941 (up to 1956). The hydrostatic pressure measuring devices are located principally along the downstream toe of the dam and at sections through the dam at sta 9+00B and 15+05B. The only data included are from those devices which have continued to function for the entire period of observation.

Description of Dam

3. Wappapello Dam is located across the St. Francis river about one-quarter mile southwest of Wappapello, Missouri. The dam was constructed by the Memphis District, CE, to control floods on the St. Francis river. It is a rolled-earth embankment about 70 ft high and 2700 ft long and has a concrete spillway and an outlet structure, both located in the right abutment. Three dikes are located north of the dam.

4. The dam was designed for a flood crest elevation of 410.4 ft mGl*. The elevation of the conservation pool is 355.0 and the top of the spillway is at el 395.0. The main embankment consists of relatively impervious fill; the embankment has a crown width of 30 ft at el 420 and has symmetrical upstream and downstream composite slopes as shown on fig. 1. The dam has ba maximum section between sta 19+00B and 19+50B where the embankment crosses the bed of the St. Francis river. At this point the embankment is 110 ft high. The stream bed was filled with compacted earth 500 ft upstream and downstream from the axis of the dam. The upstream and downstream slopes of the dam are protected with riprap. The riprap is underlain by a sand and gravel blanket except for that portion on the downstream slope above el 385 which was placed directly on the compacted earth embankment. The dam was constructed between September 1938 and May 1941. Reference The Wappapello Dam, Analysis of Design, Appendix II, Report on Soil Investigations, Memphis District, CE, 1938 and The Wappapello Dam, Plans for the Construction of Dam and Appurtenant Structures, Memphis District, CE, March 1938, for details not included in this report.

Pertinent Reservoir Stages

5. The water in the reservoir rose to el 382.7 in May 1943 and to el 399.3 in April 1945, the maximum stage observed to date. An aerial view of the dam and spillway area, obtained in April 1945 after the flood-water had discharged over the spillway, is shown on fig. 2; a view of backwater against the downstream slope is shown on fig. 3. The most recent significant high water occurred in February 1949 when the reservoir rose to el 379.

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* All elevations refer to mean Gulf level.

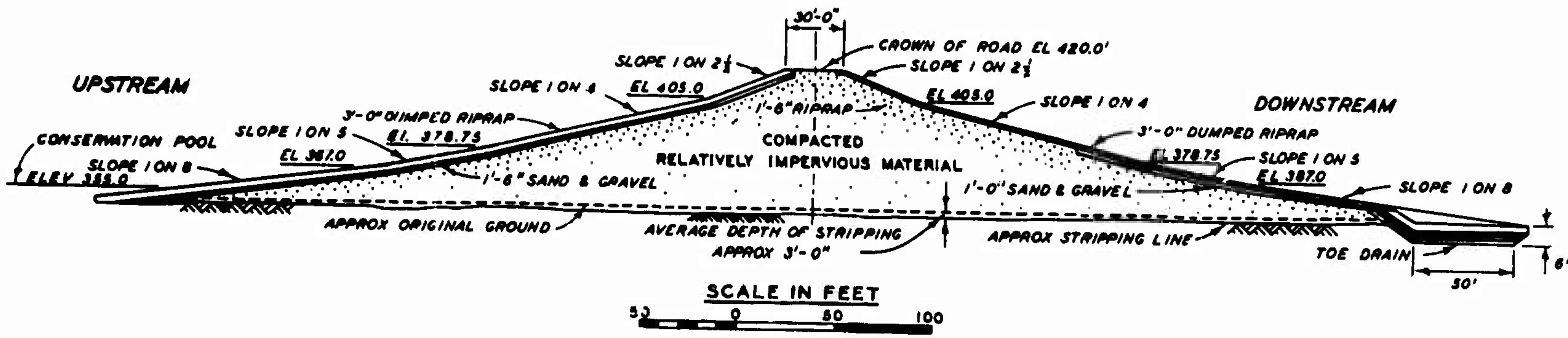

Fig. 1. Typical cross section of dam

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Fig. 2. Aerial view of dam after discharge over spillway in 1945

Fig. 3. Backwater against downstream slope of dam in 1945

PART II: FOUNDATION CONDITIONS AND TOE DRAINAGE SYSTEM

Field Exploration

6. Preliminary exploration of the foundation and dam abutments was accomplished by core and auger borings during the latter part of 1935. More extensive explorations were made by means of core borings, undisturbed borings, test pits, and exploration trenches as the design progressed. The locations of subsurface explorations along the embankment are shown on fig. 4. Logs of undisturbed and core borings along the center line of the dam are shown on fig. 5. The logs of auger borings, test pits and trenches are contained in the Analysis of Design previously referred to and are not shown in this report, as foundation conditions are adequately represented by the undisturbed and core borings.

7. As very pervious deposits of sand and gravel were known to exist deep in the foundation, an investigation was made to determine whether these strata were inclined upward upstream from the dam and outcropped in the reservoir area. Ten core borings (not shown) were made from 1000 to 2000 ft upstream of the dam center line but no outcrops of sand or gravel were found except in the river bed.

Foundation Soils

8. A generalized profile along the center line of the dam is shown on fig. 6. The generalized soil profile is based on the auger borings, test pits and trenches in addition to the borings shown on fig. 5. From the left river bank (about sta 20+00B) to the left (north) abutment (about sta 31+00B) a stratum of rather impervious silt extends 50 ft below the ground surface. This stratum is underlain by about 55 to 85 ft of alternating strata of clay and sand with some gravel extending to limestone bedrock. From the right river bank to

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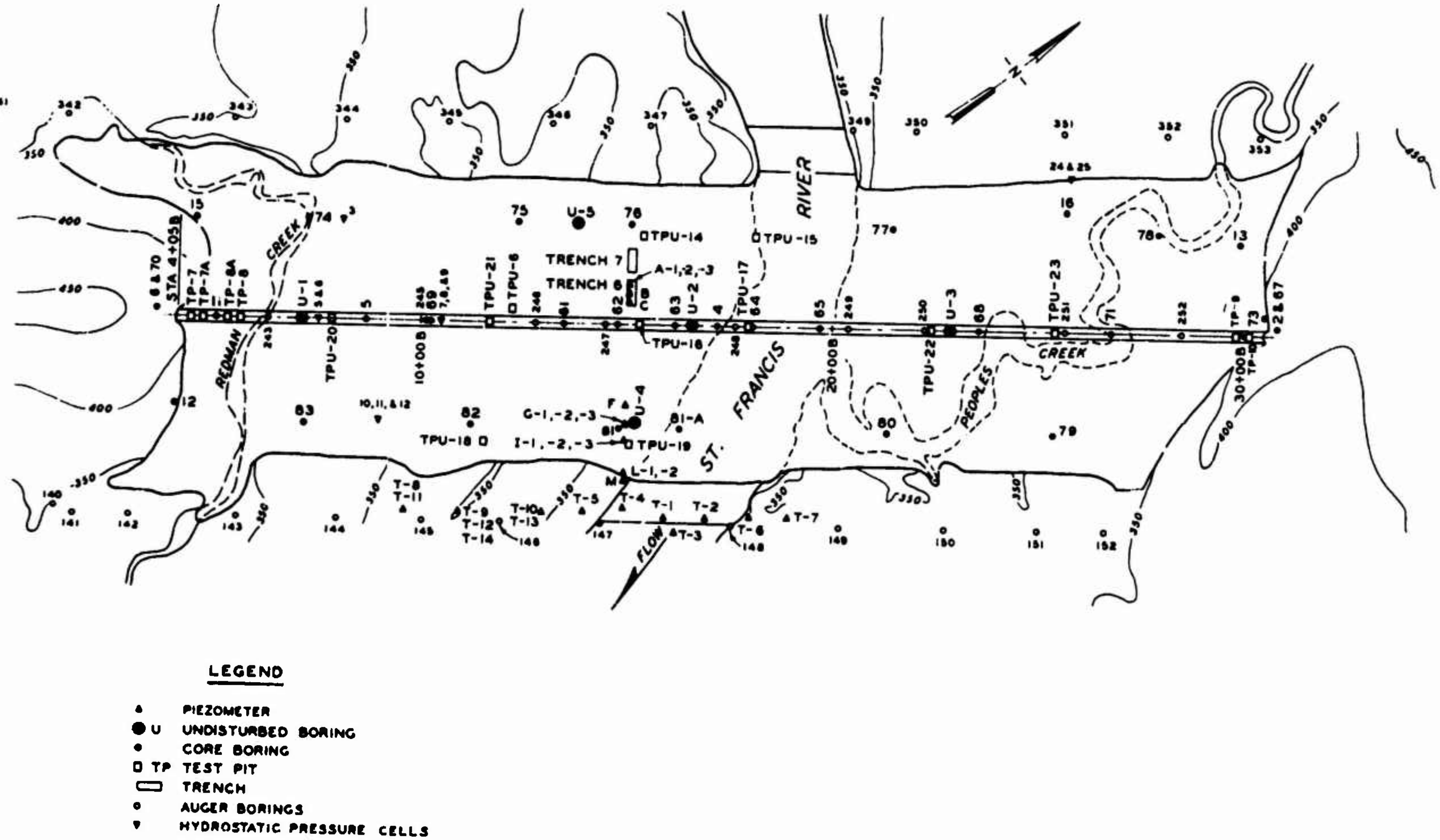

Fig. 4. Location of borings, test pits, trenches, and hydrostatic pressure measuring devices

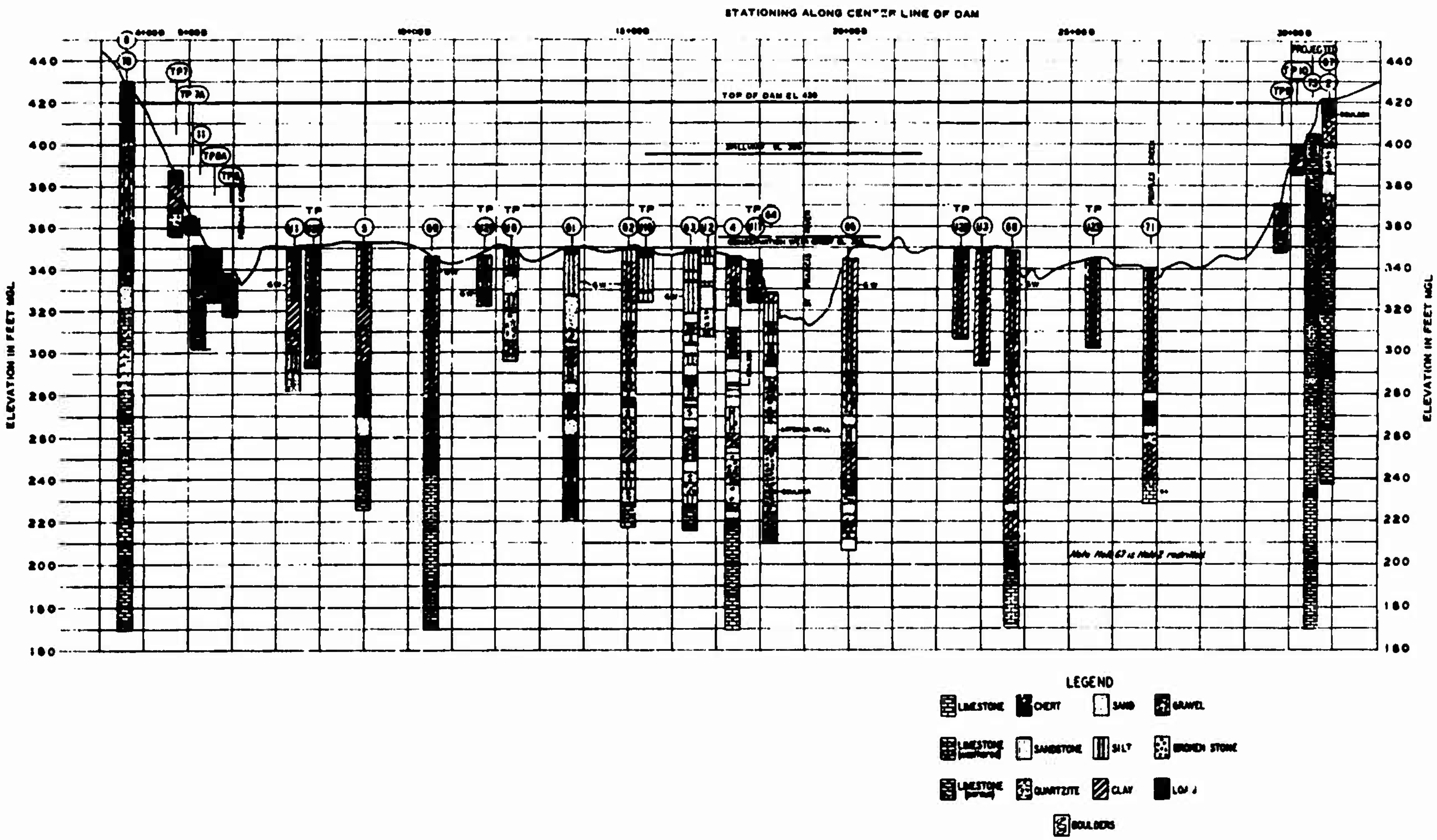

Fig. 5. Logs of borings along center line of dam

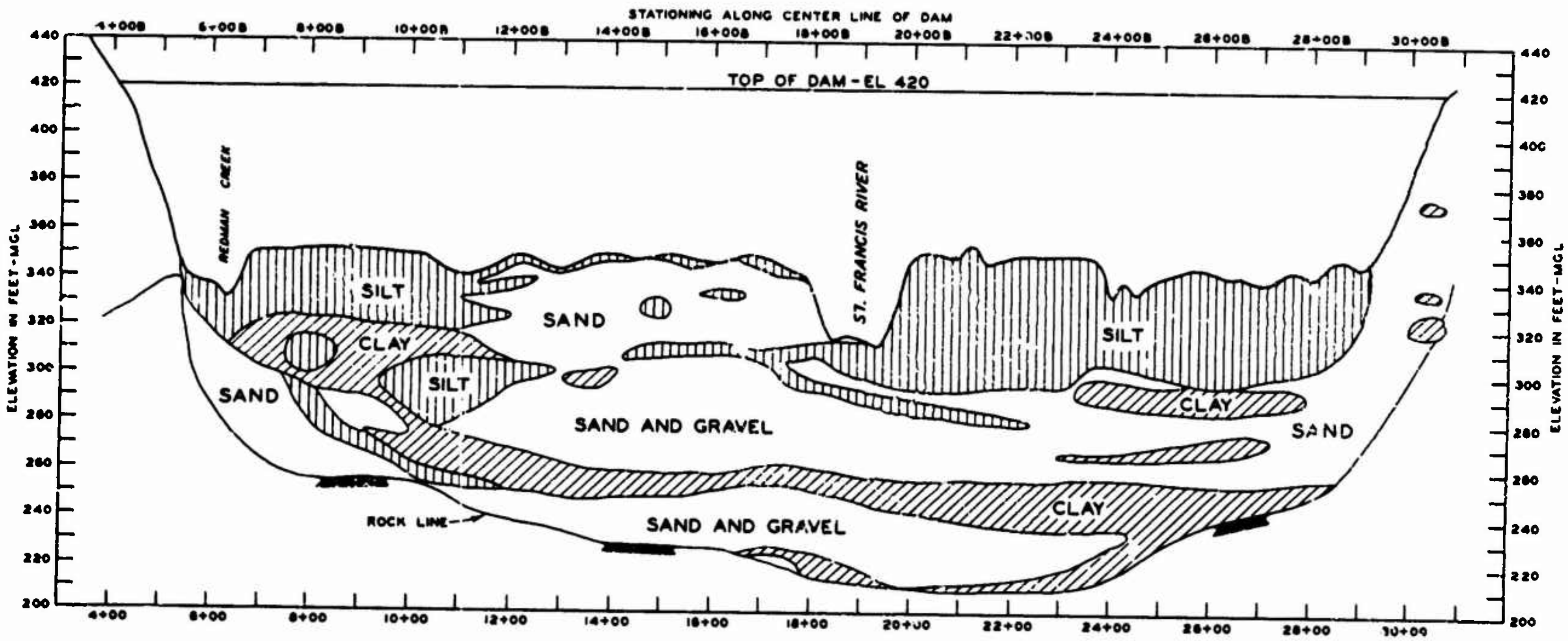

Fig. 6. Generalized soil profile along center line of dam

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approximately sta 11+00B the top stratum consists of a thin layer of silt having a maximum thickness of about 4 ft. This top stratum is generally underlain by silty sand which in turn is underlain by clean sand and gravel extending to bedrock except for a 5-ft stratum of clay at el 315 and a 10- to 15-ft stratum of clay at el 260. From sta 11+00B to the right (south) abutment a relatively impervious blanket of silt and clay 30 to 60 ft thick is underlain by a stratum of sand and gravel extending to bedrock. The rock line rises steeply as it approaches the abutments.

9. A soil profile near the downstream toe, 480 ft downstream from the center line of the dam between sta 8+00B to 20+00B, is shown on fig. 7. In this vicinity the top stratum of relatively impervious silt ranges from 3 to 10 ft thick from the right bank of the old river channel (about sta 15+00B) to about sta 10+00B. In this area the top stratum is underlain by about 20 ft of silty sand, in turn underlain by 10 ft of sand and gravel, 30 ft of clay, and 10 ft of sand and gravel. Deeper exploration was not conducted in the downstream area, but it is believed the top of bedrock is at about el 220 to 230.

Drainage System and Fill in Channel

10. A drainage system extending the length of the main embankment was placed at the downstream toe of the dam to intercept and carry off any underseepage tending to emerge in this area. Details of the toe drainage system are shown on fig. 8; a photograph of the toe drain during construction is shown on fig. 9. The toe drain has a bottom width of 50 ft and slopes of 1 on 1.5 and is located immediately upstream from the downstream toe of the dam. The toe drain consists of dumped riprap placed over a sand and gravel filter. The elevation of the bottom of the toe drainage system throughout its entire length is about el 340 except in the river channel where the bottom is at el 336.

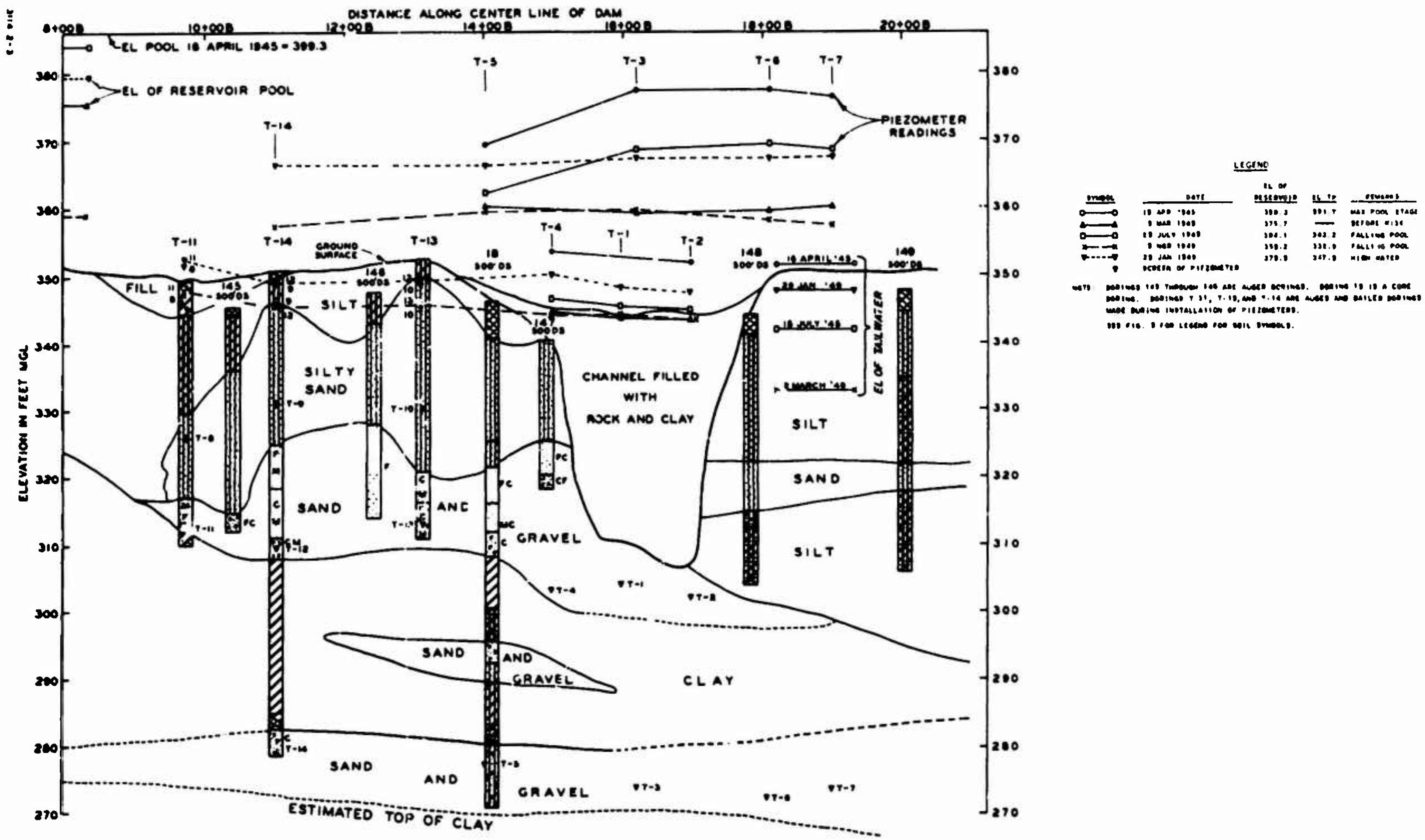

Fig. 7. Soil profile, lo..tion of piezometers, and piezometric data, 480 ft downstream from center line of dam

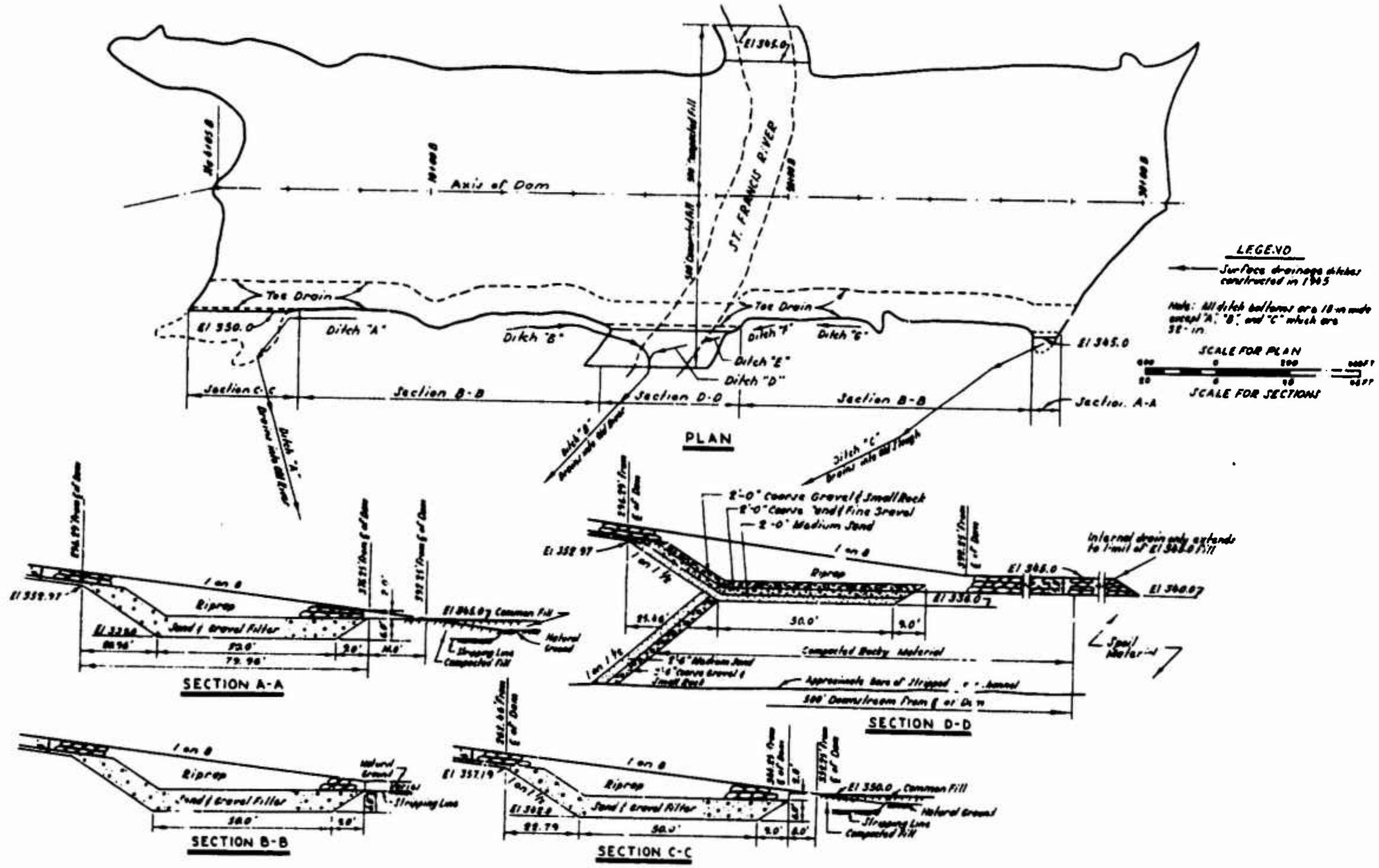

Fig. 8. Details of toe drainage system

Fig. 9. Construction of toe drain at downstream toe of dam

11. Cofferdams were constructed across the river channel and the river bed was unwatered and stripped of unsuitable materials prior to construction of the closure section. A compacted fill of an essentially impervious mixture of rock and sandy silty clay was placed in the river channel to about el 345 from 500 ft upstream to 500 ft downstream from the axis of the dam. Beyond these points for a distance of about 500 ft the river channel was filled to el 345 with the same material but the material was not compacted. The toe drain across the river channel was similar to that described above for the main embankment except that it was placed on the compacted fill. A filter blanket of 2-1/2 ft coarse gravel and 2-1/2 ft of sand was placed on the upstream face of the fill directly beneath the toe drain as shown in section D-D, fig. 8. A French drain of select rock with bottom at el 340 was placed in the center of the river fill perpendicular to the toe drain to serve as an outlet for the discharge from the toe drainage system. The French drain discharges into the old channel of the river downstream from the dam.

12. Relatively shallow surface drainage ditches were constructed in 1945 along the downstream toe as shown on fig. 8, to drain isolated low areas adjacent to the downstream toe of the dam in a direction downstream toward the old channel of the river. This was considered necessary to permit water which otherwise would tend to pond in these areas to drain readily into the old river channel downstream from the dam without having to flow through the toe drainage system. It was believed that frequent flooding of the toe drain with muddy water might eventually cause the drain to become clogged.

PART III: HYDROSTATIC PRESSURE MEASURING DEVICES

13. As the top stratum from the right bank of the river channel to sta 11+00B is relatively thin and underlain by silty and clean sands, it was believed that a potentially dangerous seepage condition might exist in this area. As the toe drain does not penetrate into the deep sand and gravel aquifer, there also was some concern regarding the development of excess hydrostatic pressure in the deepage strata, which could result in an insufficient factor of safety with respect to uplift along the downstream toe of the dam, and possible piping of foundation sands through the channel fill into the toe drain. Therefore, a system of piezometers and hydrostatic pressure cells was installed in the pervious strata beneath the downstream toe of the dam to check the actual hydrostatic pressures and their relation with reservoir pool stages. Hydrostatic pressure cells also were installed in some of the clayey strata underlying the dam, to permit the determination of the state of consolidation during and after construction, as reported in T.M. 3-398, Analysis of Settlement Data, Wappapello Dam, Missouri, Waterways Experiment Station, Vicksburg, Miss., February 1955. Piezometers also were installed within the embankment and underlying foundation at sta 15+05B to determine the pattern of seepage through and beneath the dam.

Description and Location

Piezometers

14. The original piezometer installation consisted of seven 2-in. piezometers along the downstream toe of the dam in the vicinity of the old river channel and eighteen 1-in. piezometers in the embankment and foundation of the dam at sta 15+05B. Seven more 2-in. piezometers, T-8 through T-14, were installed along the downstream toe of the dam between

the stream channel and the right abutment after the 1945 high water period. It was considered advisable to measure the pressure along this reach because of the thinness of the top stratum. Piezometers T-5 and T-7 had been leaking and were replaced in 1945. The location of all piezometers near the downstream toe of the dam is shown in plan on fig. 4 and in profile on fig. 7. Pertinent installation data for these piezometers are given in table 1; a view of some of the piezometers is shown on fig. 10. All of the 2-in. piezometers and 15 of the 1-in. piezometers are still operating. Pertinent installation data concerning the 1-in. piezometers at sta 15+05B are given in table 2. A cross-section of the dam at sta 15+05B with the locations of these piezometers is shown on fig. 11.

Hydrostatic pressure cells

15. Six Foxboro, 12 Goldbeck, and 51 Wilson cells were installed during construction. About 20 of the 69 cells failed soon after installation and only 9 were still operating in January 1956. The location and type of cells still functioning are given in table 3. The locations of these cells are shown in plan on fig. 4. Seven of the cells still functioning are located near sta 9+COB and are shown on the cross-section of the dam on fig. 12; the other two cells still functioning (24 and 25) are located at sta 25+80B. The three types of hydrostatic pressure cells are described in the following paragraphs.

16. Goldbeck cells. The Goldbeck* cell consists of disk-shaped metal case in one end of which a movable metal piston is held flush with the rim of the case by a thin metal diaphragm. A perforated plate is attached over the piston and diaphragm to permit only hydrostatic pressure to activate the cell. The entire device is approximately 5-1/2 in. in diameter by 1-1/4 in. thick. Electrical contact is made between the movable piston and an insulated electrical contact button which is fastened inside the case. Compressed air is introduced in

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* Goldbeck, A.T., and Smith, E.B., An Apparatus for Determining Soil Pressures, Proceedings, ASTM, vol 16, no. 2, pp 310-319, 1916.

Table 1

Location of Piezometers Along Downstream Toe of Dam

Piezometer	Station	Distance from Center Line ft	Elevation Center of Screen mGl
T-1	16+03B	483	303.7
T-2	17+03B	482	301.8
T-3	16+26B	521	273.9
T-4	15+03B	459	302.9
T-5	14+04B	472	277.2
T-6	18+12B	479	272.1
T-7	19+05B	480	273.4
T-8	9+68B	475	325.7
T-9	11+05B	475	330.9
T-10	13+05B	475	330.0
T-11	9+68B	480	312.2
T-12	11+05B	485	309.5
T-13	13+05B	480	312.7
T-14	11+05B	480	278.9

NOTE: Piezometers consist of 2-in. riser pipe with a 2-in. wellpoint screen at lower end. Length and type of wellpoint screen are not known.

Table 2

Location of Piezometers at Sta 15+05B

Piezometer	Distance from Center Line ft	Elevation Center of Screen mGl	Type
A-1	100 US	350.0	A
A-2	100 US	364.8	A
A-3	100 US	379.9	A
B	80 US	369.9*	B
C	60 US	360.9*	B
F	200 DS	346.0*	B
G-1	250 DS	307.2	A
G-2	250 DS	325.4	A
G-3	250 DS	339.8	A
I-1	290 DS	307.8	A
I-2	290 DS	329.9	A
I-3	290 DS	340.2	A
L-1	370 DS	310.1	A
L-2	370 DS	329.9	A
M	390 DS	320.0*	B

* Indicates bottom of perforated section.

NOTE: Type A piezometers consist of 1-in. riser pipe with a 6-in. long tip made of No. 65 brass screen with 1/8-in. holes drilled in the screen on 1-in. centers. The tip was placed in a 6-in. hole and surrounded by scarse sand from the bottom of the tip to 2 ft above the bottom of the tip.

Type B piezometers consist of 1-in. pipe perforated throughout its length. The size and number of perforations are not known.

Table 3

Location of Hydrostatic Pressure Cells

Cell	Station	Distance from Center Line ft	Elevation	Type Cell
3	8+05B	250 upstream	341.3	Goldbeck
7	10+50B	center line	284.9	Foxboro
8	10+50B	center line	304.5	Foxboro
9	10+50B	center line	327.9	Foxboro
10	9+00B	250 downstream	280.9	Foxboro
11	9+00B	250 downstream	305.0	Foxboro
12	9+00B	250 downstream	333.4	Foxboro
24	25+80B	390 upstream	300.2	Goldbeck
25	25+80B	390 upstream	319.9	Goldbeck

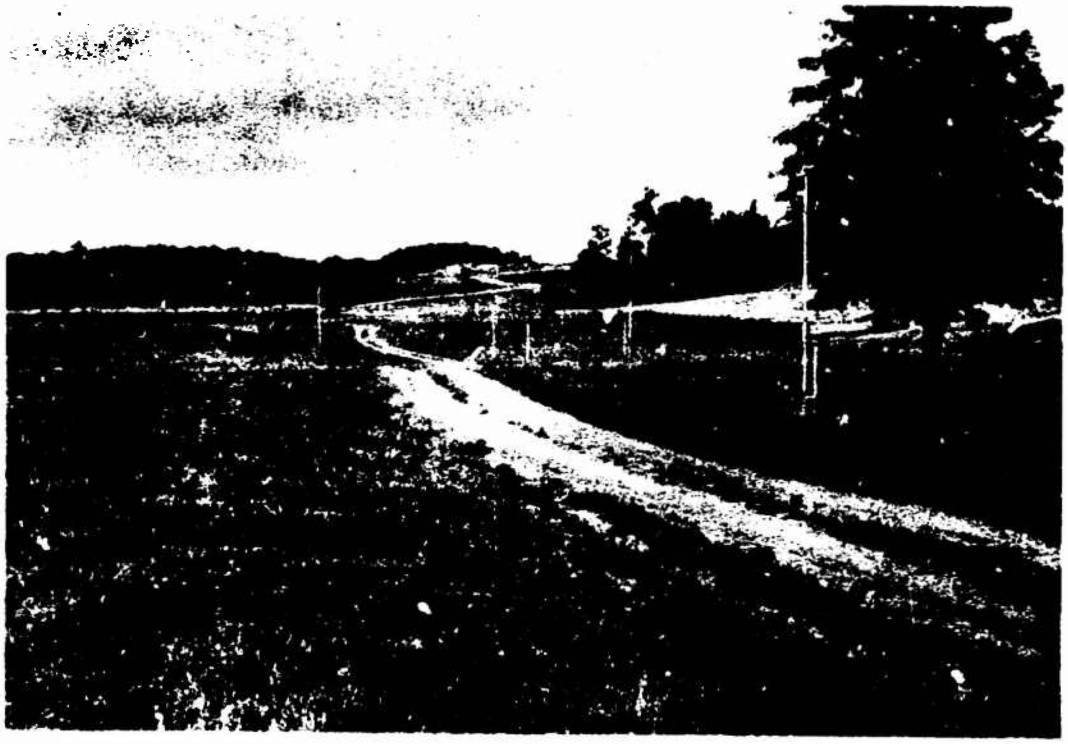

Fig. 10. View of piezometers along downstream toe of dam

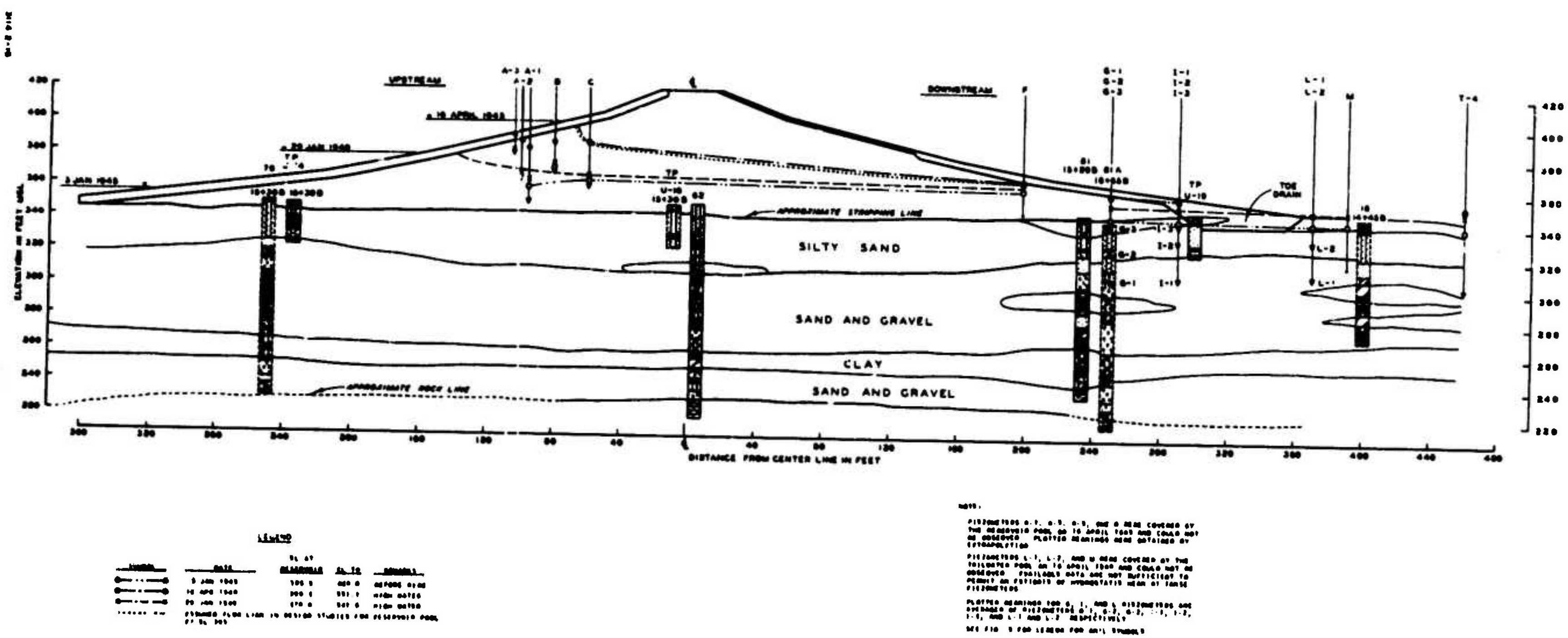

Fig. 11. Cross section, location of piezometers, and piezometric data, sta 15+05B

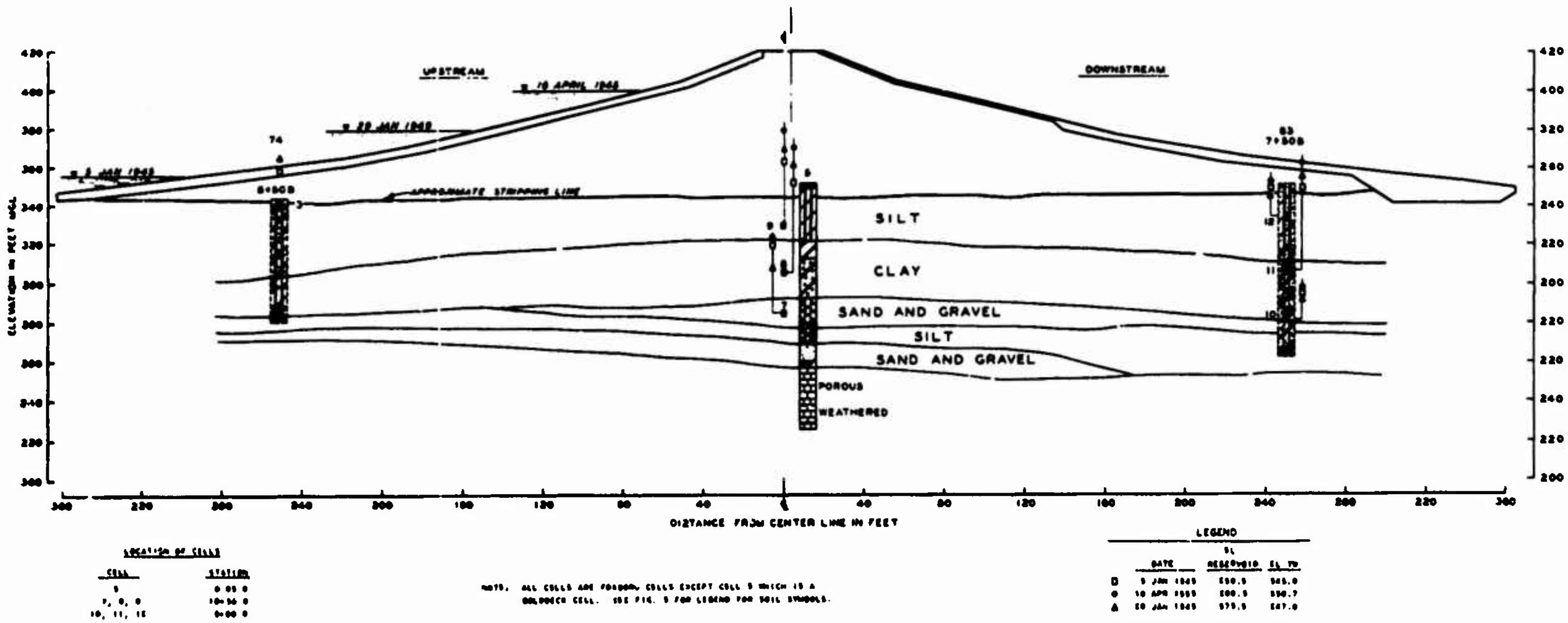

Fig. 12. Cross section and location of hydrostatic pressure cells, sta 9+00B

the cell to equal the external pressure acting on the piston and pressure-sensitive diaphragm of the cell. Two pipes extend from the cell to the surface, one conveying compressed air to the cell, the other protecting an insulated wire connected to a milliammeter at the surface. The diaphragm deflects and the electric circuit is broken when the induced compressed air equals the external hydrostatic pressure. When the open circuit is observed on the milliammeter, the air pressure is noted and is assumed to be equal to the hydrostatic pressure at the gauge (acting on the cell).

17. Wilson cells. The Wilson* cell is similar in appearance and operation to the Goldbeck cell except that an air escape valve is substituted for the electric circuit breaker and an exhaust pipe is used instead of the insulated wire of the Goldbeck cell. Compressed air is introduced into the cell to equal the external hydrostatic pressure. When the pressure inside the cell equals the hydrostatic pressure, it opens the valve which permits the compressed air to enter the exhaust pipe and leak under constant pressure into a bottle of water. A gauge on the compressed air line is read when air bubbles are first detected in the bottle.

18. Foxboro cells. The Foxboro** cell records directly the hydrostatic pressure acting on the cell. The device consists of a metal box approximately 4-3/4 in. by 2 in., divided into two parts by a pressure-sensitive diaphragm. The bottom portion of the box is perforated which permits a hydrostatic head to act on the diaphragm and compress the air in the upper protion of the box, which is connected by tubing to a pressure gauge. The pressure inside the cell is read from the gauge and is assumed equal to the external hydrostatic pressure acting on the cell.

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* Corps of Engineers, Memphis District, Instructions for Calibration and Use of Wilson Type Earth and Hydrostatic Pressure Cells, Memphis Tenn., 29 May 1939.

** The Foxboro Company, Liquid Level Instruments, Bulletin No. 392.

PART IV: OBSERVATIONS AND ANALYSIS OF DATA

Schedule for Readings

19. The various hydrostatic pressure measuring devices were observed according to the schedule given below. Observations were made frequently until September 1943 at which time the schedule was changed to permit less frequent observations.

Dates	Device	Frequency of Observations	
1941	Piezometers, downstream toe	semiweekly	
to	Piezometers, sta 15+05B	weekly	
1943	Pressure cells	weekly	
		Reservoir Stage	
		Normal	High
Sept 1943	Piezometers, downstream toe	bimonthly	daily
to	Piezometers, sta 15+05B	semiannually	daily
Jan 1957	Pressure cells	semiannually	daily

The above schedule of observations generally has remained unchanged since 1943. However, between September 1943 and July 1944 the high reservoir stage at which daily observations were begun was taken as el 368. In July 1944 this elevation was changed from el 368 to el 375.

Piezometers at Downstream Toe

20. The piezometers installed at the downstream toe at approximately the same elevation and in the same kind of material have been grouped together for the purpose of plotting the piezometer readings and the corresponding reservoir pool stages vs time. The average readings of these piezometer groups are plotted vs time on figs. 13 and 14. Locations of these piezometers are shown in profile on fig. 7.

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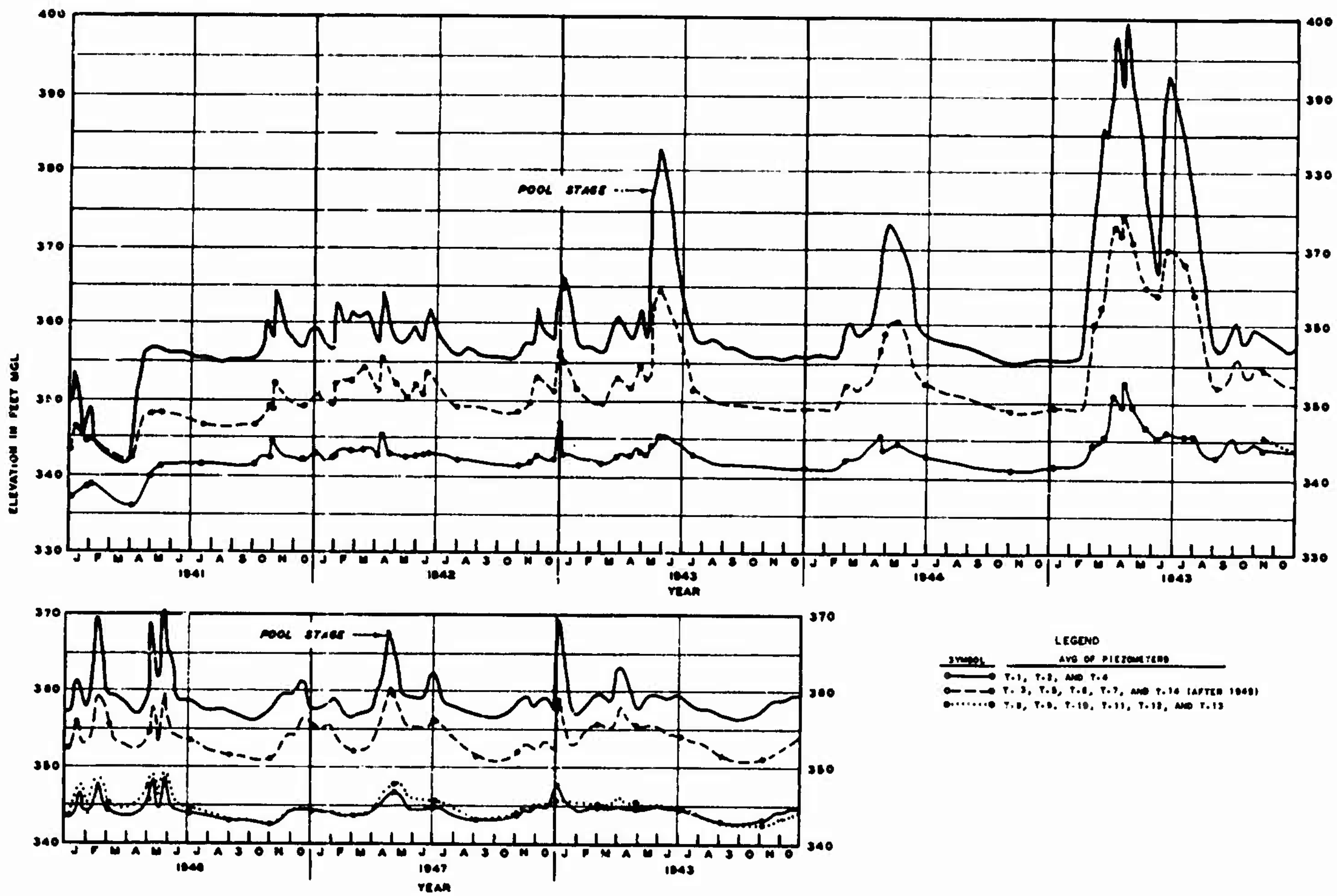

Fig. 13. Data from piezometers near downstream toe of dam, 1941-1948

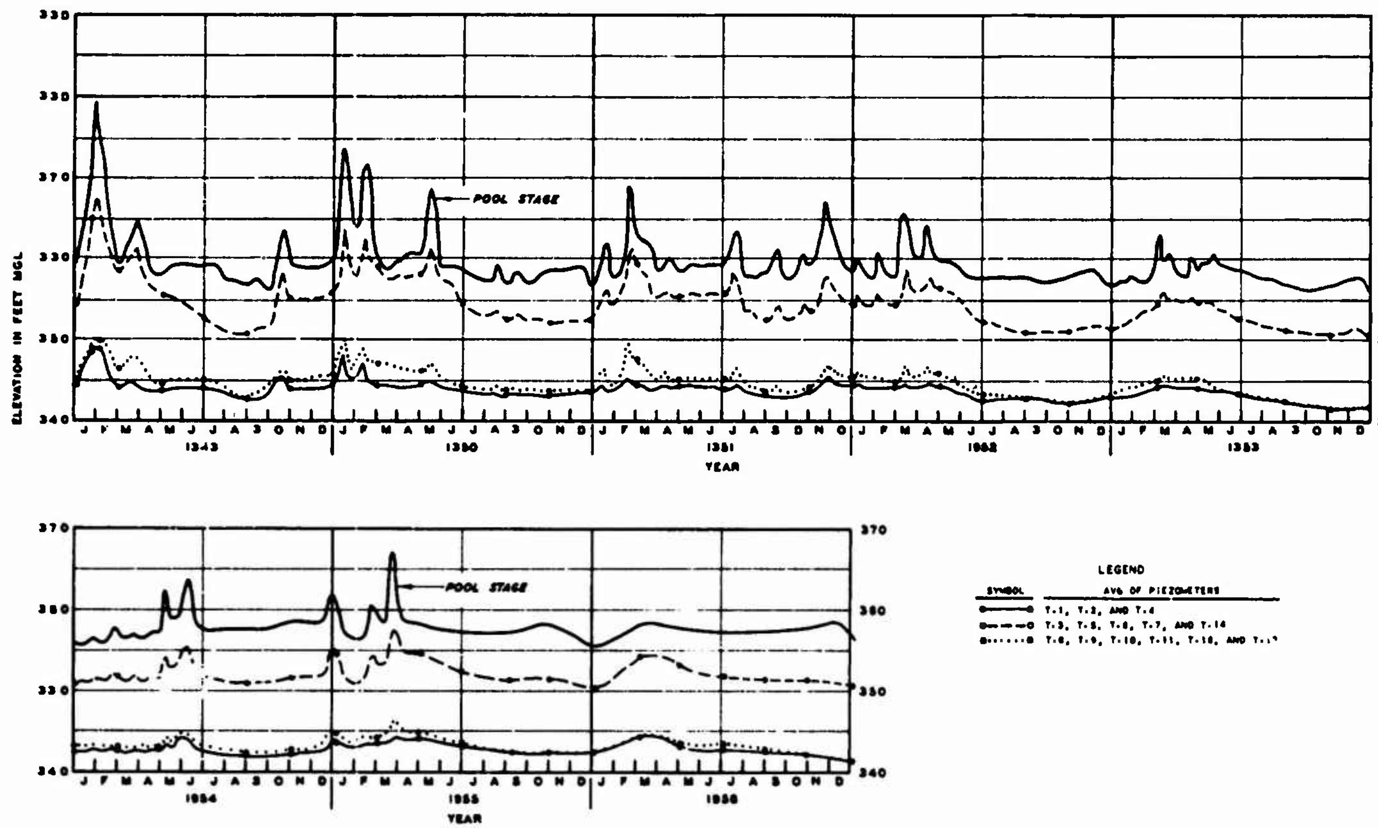

Fig. 14. Data from piezometers near downstream toe of dam, 1949-1956

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One group, T-3, -5, -6, -7, and -14, lies in the deep sand at about el 274. Another group, T-1, -2, and -4, is in the sand and gravel strata beneath the old channel at about el 304. The third group, T-11, -12, -13, lies in the shallower sand and gravel between the old channel and the right abutment at about el 311. The fourth group, T-8 through -10, lies in the silty sand beneath the top stratum between the old channel and the right abutment at about el 329, just above the third group.

21. It may be seen from figs. 13 and 14 that the average readings of piezometers in a given stratum reflect changes in the reservoir, the piezometers in deep sand and gravel strata being more sensitive to the rise and fall of the reservoir than the shallow piezometers. There is close agreement between average readings of piezometers T-11 through -13, located in the upper sand strata, and piezometers T-8 through -10 located directly above the upper sand strata.

22. Readings for typical piezometers installed in the sand and gravel strata at about el 272 and 303 and at el 330 in the silty sand stratum are plotted vs reservoir pool stage on fig. 15 for years in which the reservoir pool stage was relatively high. The sequency of readings also is shown on fig. 15 and it can be noted that at high reservoir pool stages the readings at a given pool elevation generally are higher for a falling reservoir stage than for an increasing stage. The relationship between piezometer readings and reservoir pool stage is fairly consistent during the periods for which data are shown, indicating that the effective source of seepage entry was relatively constant.

23. Piezometric profiles along the downstream toe of the dam are shown on fig. 7 for pertinent maximum reservoir stages and for rising and falling pool stages. This figure shows that the piezometers with tips at about the same elevation read approximately the same on a given date. During the high reservoir stage in 1945 the excess

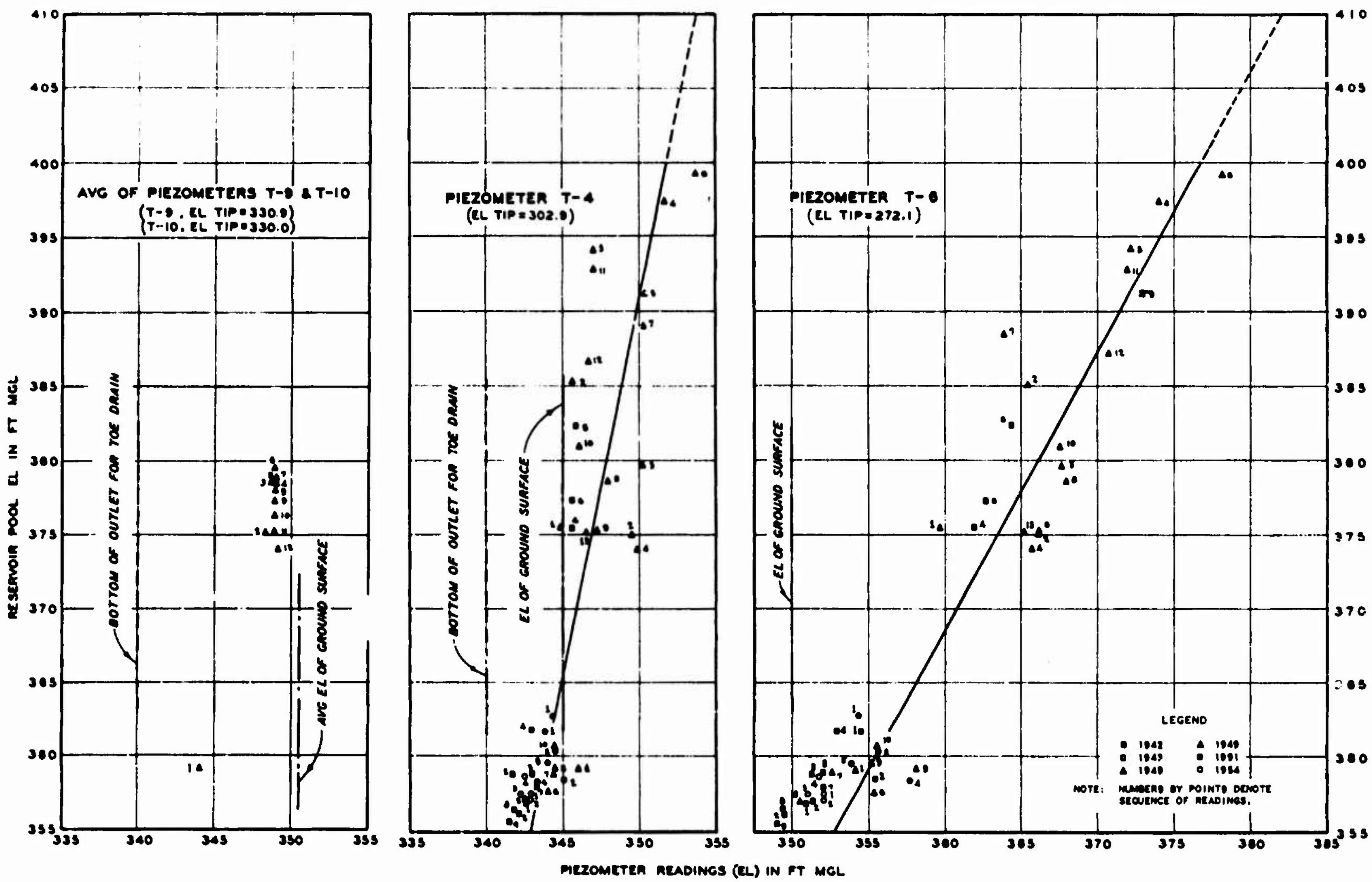

Fig. 15. Readings of typical piezometers vs reservoir pool elevation

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hydrostatic head in the deep sand and gravel below el 280 was approximately 25 ft or about 50 per cent of the net head on the dam. The excess hydrostatic head in the upper sand and gravel stratum was considerably lower, ranging from 1 to 3 ft. Piezometers installed after the 1945 high pool stages in the silty sand stratum underlying the top stratum indicated that the hydrostatic head in the silty sand stratum is essentially the same as that existing in the underlying upper sand and gravel stratum. The bottom of the downstream toe drainage system extends into the silty sand stratum between the river channel and right abutment. Consequently it appears that significant pressure relief is provided by the toe drainage system.

24. The effectiveness of the toe drain is further illustrated by the variation in hydrostatic head with depth, as shown on fig. 16. Readings of piezometers T-9, -12, and -14 for three reservoir stages are plotted on fig. 16. These piezometers are at sta 11+05B but at different elevations. It may be seen that there is a large drop in pressure between T-14, located in the deep sand and gravel, and T-12, located in the upper sand and gravel stratum. There is little difference in pressure between T-12 and T-9 which is located in the silty sand stratum overlying the upper sand and gravel. Also shown on fig. 16 is the estimated pressure in the foundation strata with the reservoir pool at el 410. The estimated pressure was based on extrapolation of data shown on fig. 15 for piezometers in the same strata as those shown on fig. 16. On the basis of data shown on fig. 16, little excess hydrostatic head will exist in the upper pervious strata for reservoir stages as high as el 410. Therefore, it is considered that the top stratum along the downstream toe is safe against failure due to uplift for the maximum reservoir pool.

25. During an inspection trip in July 1955 it was noted that piezometer T-3 was flowing. It was pointed out that this was undesirable, as the readings obviously would be affected and continuous

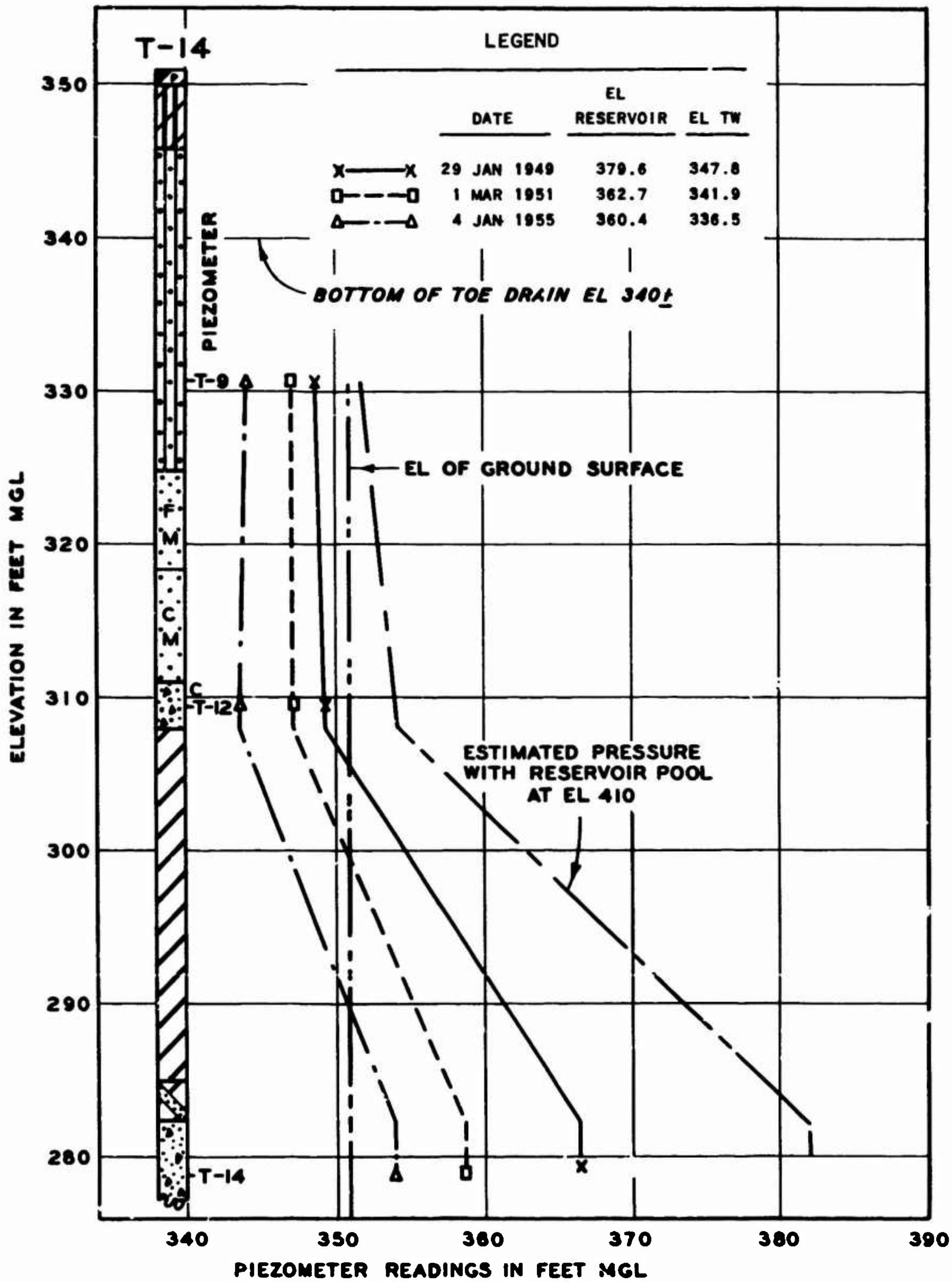

Fig. 16. Hydrostatic pressure near downstream toe of dam vs depth, sta 11+05B

flow might also be conducive to more rapid corrosion of the piezometer. It was also noted that piezometer T-5 had a leaking discharge valve; the discharge past the closed valve was almost the same as when it was open. Leakage of this discharge valve probably accounts for the fact that piezometer T-5 shortly before 1955 read generally lower than other piezometers installed in the same stratum. Questionable readings of piezometer T-5 were not used in pertinent analyses in this report. All other piezometers appeared to be leakproof and operating satisfactorily.

26. Upward hydraulic gradients. Upward hydraulic gradients were computed from the readings of piezometers along the downstream toe of the dam made during 1945 and 1949. The computed gradients are plotted vs reservoir pool elevation on fig. 17. Gradients were computed from the bottom of the clay stratum at el 280 to ground surface using an average excess hydrostatic head based on piezometers in the lower sand and gravel stratum (T-3, -5, -6, and -7). Gradients also were computed from the bottom of the river channel to ground surface, using average excess hydrostatic pressures from piezometers T-1, -2, and -4. Gradients from the bottom of the clay stratum at el 280 to ground surface during the 1945 high water period ranged from about 0.31 to 0.38 as shown on fig. 17. These gradients will be about 0.45 at the maximum reservoir pool and indicate that the pressures probably are not high enough to cause any uplift or blow-out. Gradients from the bottom of the channel fill to ground surface ranged from 0.02 to 0.06 in 1945 and probably will be about 0.07 at the maximum reservoir pool.

27. Piezometers T-1 through T-7 were installed primarily to observe the upward hydraulic gradient into the filled river channel. The channel is underlain by fine sand. If the hydraulic gradient through the fine sand should approach the critical gradient (about 0.9) it was originally thought the sand might pipe into voids in the channel fill. Gradients immediately beneath the channel fill were computed assuming that the excess hydrostatic head indicated by piezometers T-1,

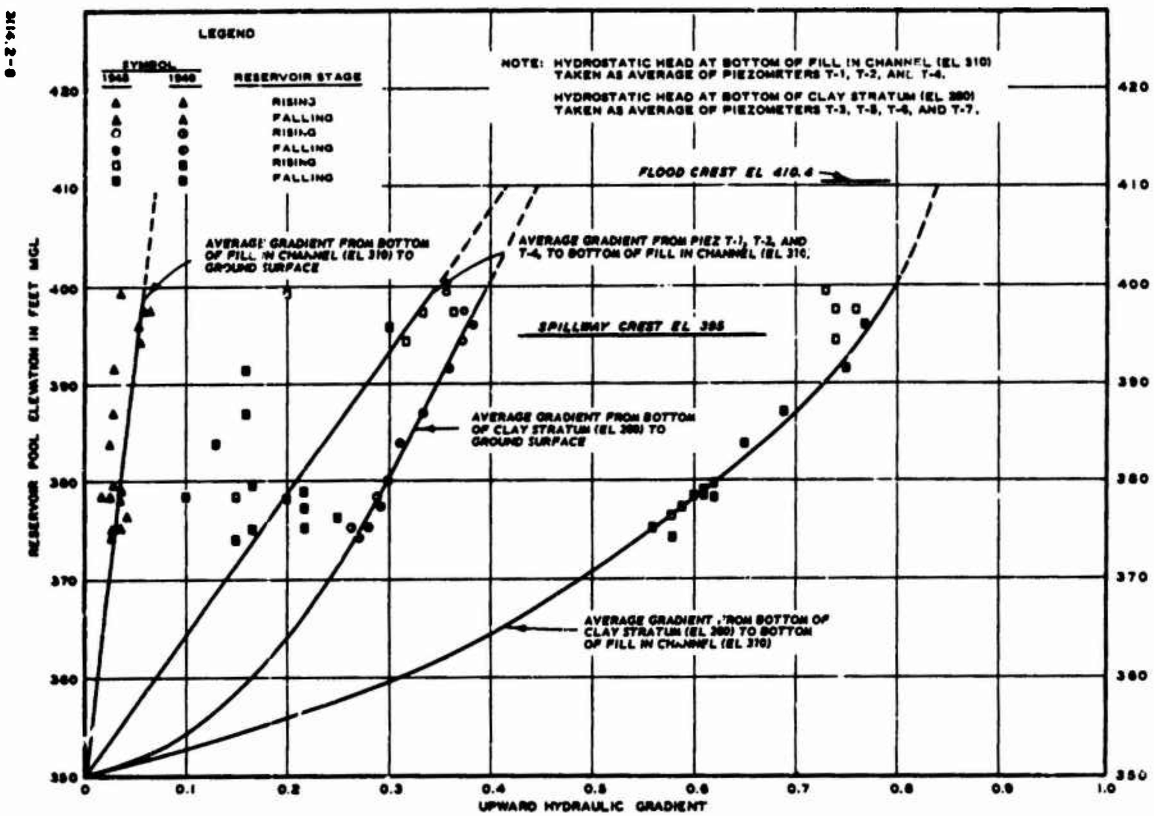

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Fig. 17. Upward hydraulic gradients through foundation along downstream toe of dam

-2, and -4 was dissipated between the piezometer tips and the bottom of the channel fill. The upward hydraulic gradients computed in this manner are shown for various reservoir pool stages on fig. 17. In 1945 the gradients ranged from about 0.16 to 0.36. With the reservoir at maximum pool this gradient will be about 0.42, indicating the piping into the channel fill is unlikely. Furthermore, the channel fill material is believed to be relatively impervious, consisting of rock and clay, which would lessen further the possibility of piping. That the fill is relatively impervious is confirmed by the fact that pools of rainwater 1-1/2 ft above the level of the tailwater have been observed standing in the old channel near the toe of the dam during periods of high water. Gradients were computed also from the bottom of the clay stratum at el 280 to the bottom of the channel fill as shown on fig. 17. The computed gradient for maximum reservoir pool stage will be about 0.84. However, there is little likelihood of dangerous piping under this gradient, because it is believed the clay stratum is continuous between el 280 and about 300. The dam safely withstood a high water stage of el 399 (4 ft above spillway crest) creating a gradient of 0.75.

28. The most critical area for piezometers installed after the high reservoir period in 1945 (T-8 through T-14) would appear to be at piezometer T-10 at sta 13+05B where there is only about 3 ft of top stratum. Available data since the high pool stage in 1945 are not sufficient to permit an estimate of the reading of piezometer T-10 and corresponding gradient for a reservoir stage of 410. However, as readings of this piezometer vary little with reservoir pool and generally are about 2 ft below the ground surface (fig. 15), it is probable that little to no excess head will develop at this piezometer.

Piezometers at Sta 15+05B

29. The locations of piezometers and seepage observation wells at sta 15+05B are shown on fig. 11. Readings of piezometers at sta 15+05B are plotted chronologically with corresponding reservoir stages on figs. 18 and 19. Available tailwater data are shown on fig. 18; sufficient data are not available to permit plotting a continuous record of tailwater elevations on this figure. Generally, the readings of piezometers A-1, -2, -3, B and C were higher than the reservoir pool and therefore a continuous plot for these piezometers is not shown on fig. 18. The fact that the readings of these piezometers generally are higher than the reservoir pool during low pool stages is attributed to the piezometers possibly being affected by capillary moisture, rainfall, and other factors. The readings of piezometer F also may be affected by surface runoff through the riprap on the downstream slope of the dam as the screen of this piezometer extends up through the riprap. Generally, the piezometer levels rose and fell with corresponding reservoir stages when the reservoir pool was about the tip of the piezometer; readings for the 1945 and 1949 high water periods and for the low water period prior to the rise of 1945 also are shown on fig. 11. Available piezometric data are not sufficient to estimate the distance to the effective source and exit of seepage. The A and B piezometers on the upstream side of the dam generally were submerged during the high water period and readings were not made. However, some readings of the A and B piezometers were obtained at high pool stages in 1945 before these piezometers became submerged. Readings for piezometers in each of the G, I, and L groups were approximately the same for each piezometer in the group for any given date. The line of seepage within the embankment for each of the above dates as approximated from the piezometer readings is shown on fig. 11. These lines of seepage are considered only approximate because many

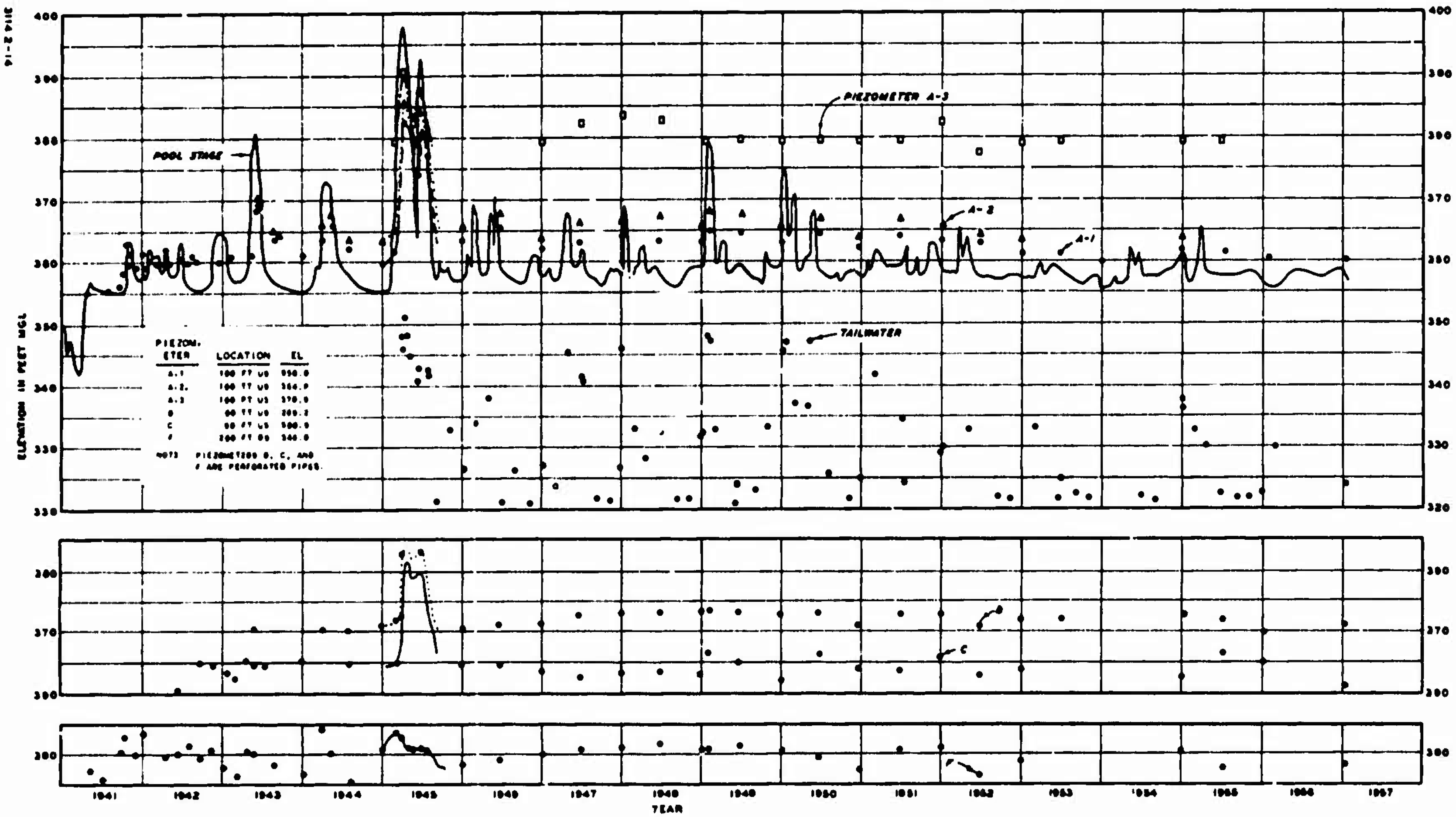

Fig. 18. Data from piezometers at sta 15+05B, piezometers A, B, C, and F

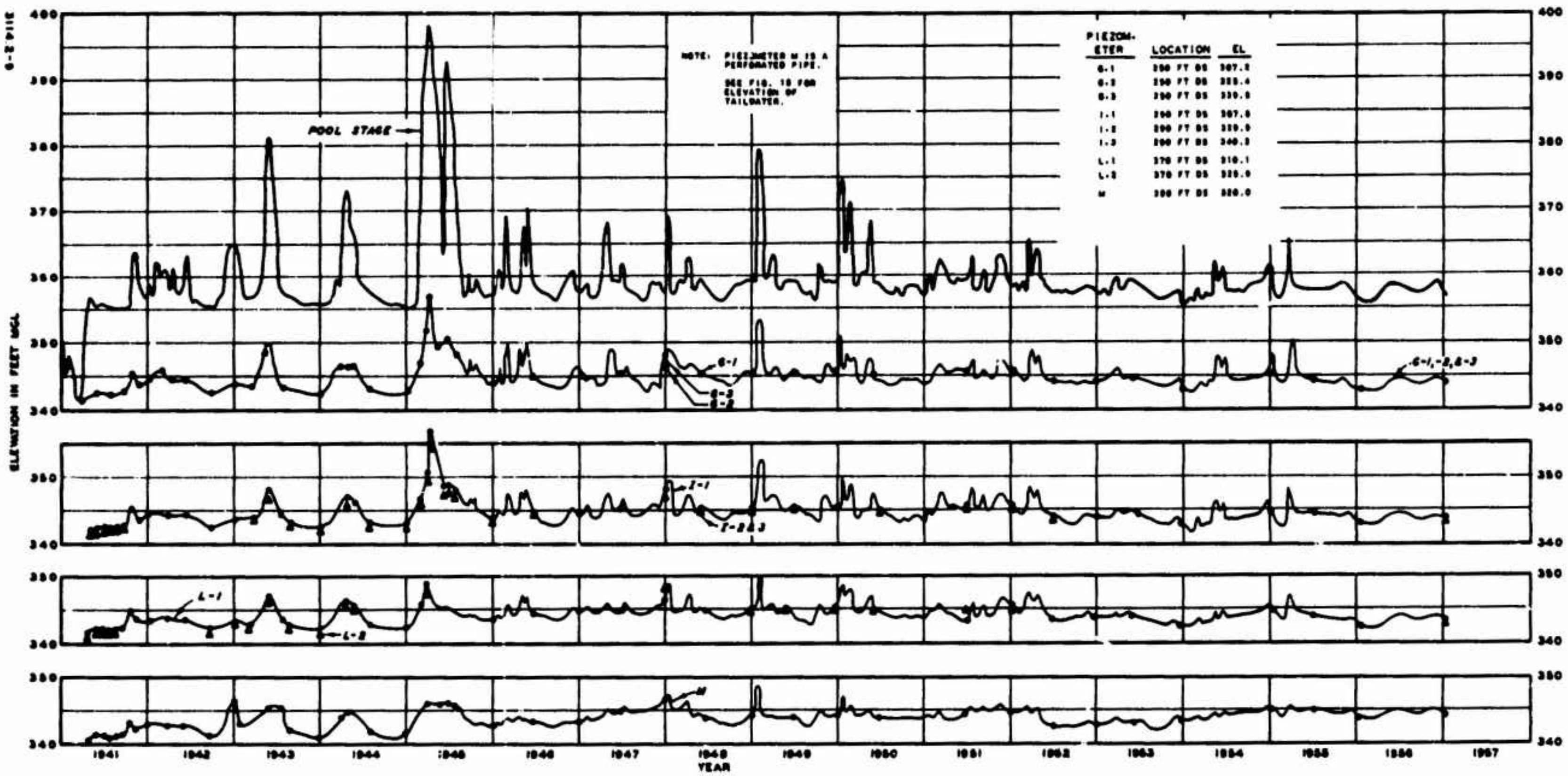

Fig. 19. Data from piezometers at sta 15+05B, piezometers G, I, L, and M

of the piezometers at sta 15+05B appear to be affected somewhat by rainfall and other factors. Also shown for comparison is the uppermost flow line (phreatic line) for the reservoir pool at el 395 assumed for design purposes. The line of seepage through the embankment could not be traced to the downstream toe beyond piezometer F; however, it appears tha that the seepage may pass into the riprap on the lower face of the dam and thence into the toe drain. As no emergence of seepage was observed on the downstream face of the dam during the high water period of 1945, the dam is believed safe with respect to uncontrolled emergence of seepage through the embankment. It is considered that continuation of the observations of piezometers at sta 15+05B would not provide additional data of consequence and that future observations are not warranted.

Hydrostatic Pressure Cells

30. Readings of those hydrostatic pressure cells still functioning are plotted chronologically with reservoir stages on fig. 20. Data from cells 24 and 25, which appear to be giving consistent readings, are not shown on fig. 20, as they are located near the upstream toe of the dam and are not pertinent to the problem of underseepage. It may be noted from fig. 20 that the readings of cells 7 and 10 have decreased with time to such extent that it is doubtful if the cells still are functioning properly. Hydrostatic pressure cell readings for the 1945 and 1949 high water periods and for the low water prior to the rise of 1945 are shown on fig. 12. It may be noted that the majority of the cells are located in relatively impervious soil strata and accordingly would not be expected to reflect quickly the excess hydrostatic pressures in the sand foundation due to high reservoir stages. As the cells still functioning are mainly those installed to determine foundation pore pressures caused by consolidation, they offer little

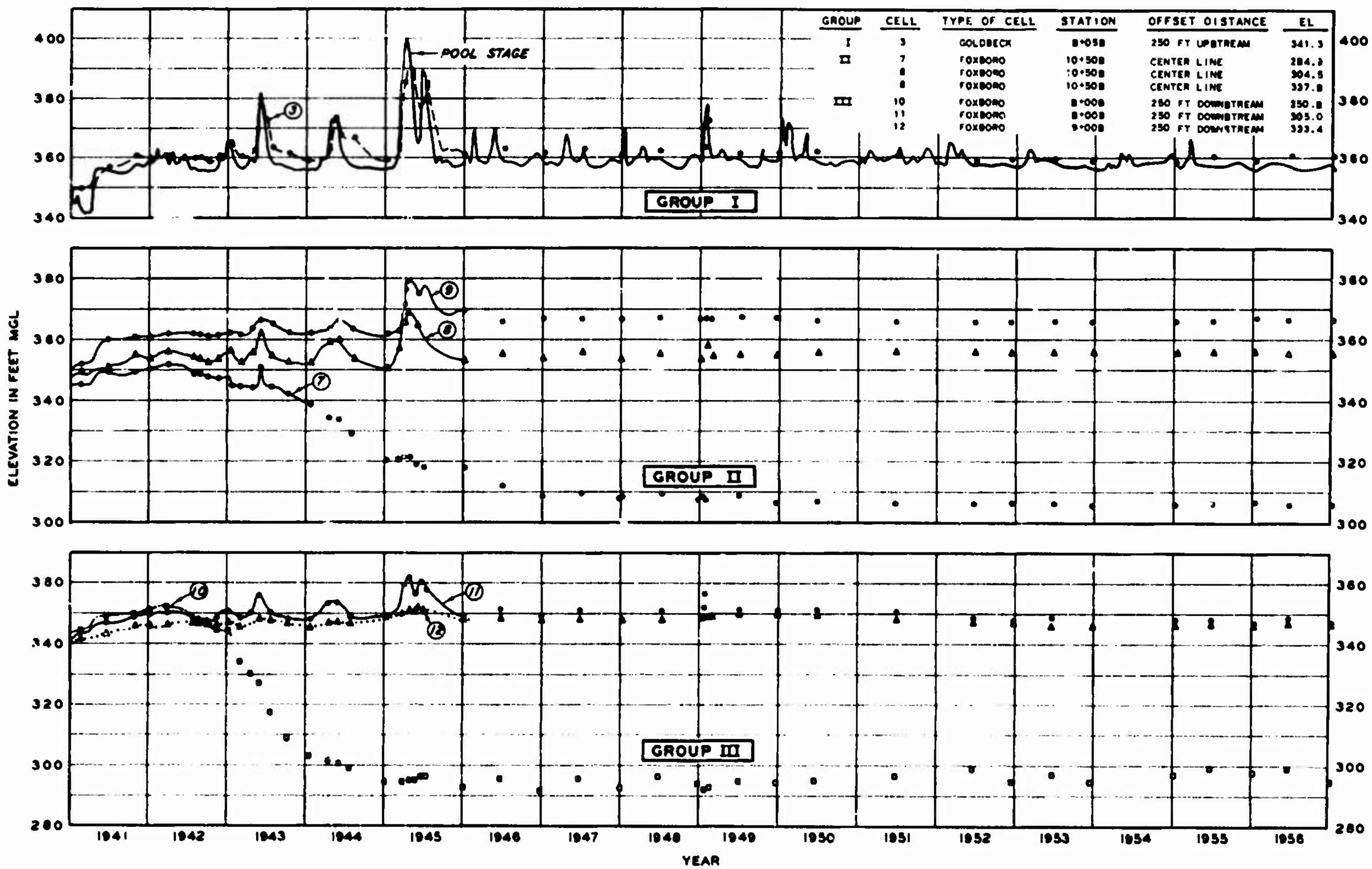

Fig. 20. Data from hydrostatic pressure cells

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pertinent data from the standpoint of underseepage. Foundation conditions at sta 9+00B are complex and no attempt was made to evaluate the significance of the observed hydrostatic heads as measured by the pressure cells. As settlement observations indicate that the dam foundation is completely consolidated as of this date (1957) there appears to be no need for further observations on the hydrostatic pressure cells.

Seepage Measurements

31. The amount of seepage intercepted by the toe drainage system was measured at the end of the French drain, which discharges downstream from the toe of the dam in the river channel. A sand bag dike was constructed at the end of the drain, a pipe was placed in the dike and the amount of water discharging through the pipe was measured. Seepage measurements were made during the last part of 1941 and early part of 1942 when the reservoir pool varied from el 355 to 360. The observed flows ranged from 36 to 227 gpm. Seven seepage measurements were made during the period 7-22 March 1945 when the elevation of the reservoir varied from 384 to 388 and was rising. The measured seepage varied from about 230 to 390 gpm. The elevation of the water in the area inclosed by the sand bag dike was not determined at the time of the seepage measurements; however, it is estimated that this water was at about el 340.

32. A plot of seepage discharge vs reservoir pool elevation is shown on fig. 21. The seepage measurements vary so much for such a small range in reservoir elevation that they can be related only approximately to reservoir pool elevation. On the basis of fig. 21 it appears that seepage beneath the dam is equivalent to approximately 6.5 gpm per foot of net head above tailwater (el 340 $\pm$). It is believed that most of this seepage enters the toe drainage system along

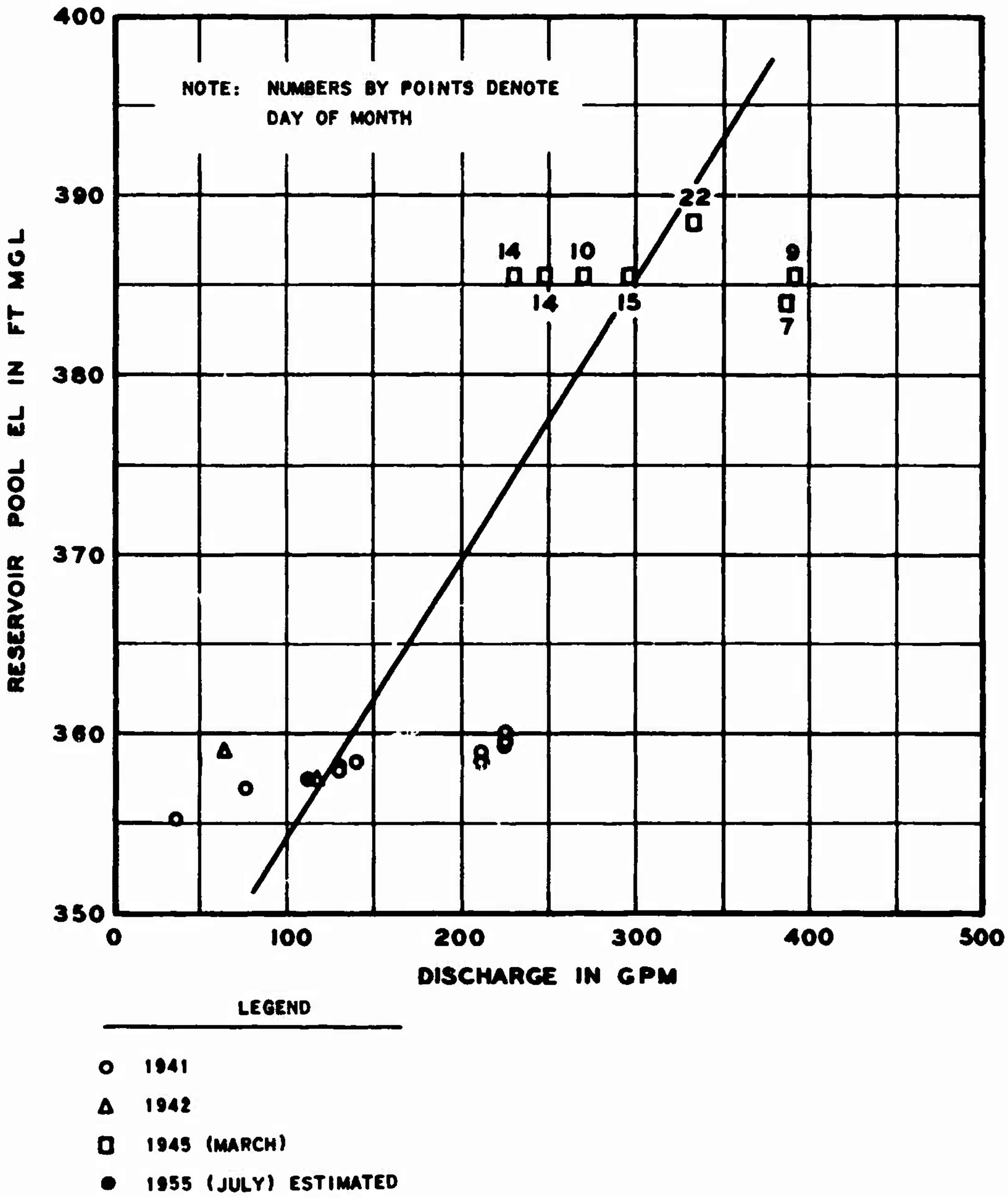

Fig. 21. Measured seepage from toe drain

the downstream toe of the dam between the right bank of the river channel (about sta 15+00B) and the right abutment, as the toe drain does not penetrate into pervious foundation strata left of the river channel and the compacted fill in the river channel apparently is relatively impervious. It is not possible to determine what percentage of the total flow the observed seepage represents, in view of the heterogeneity and complexity of the foundation conditions. The amount of seepage is not considered excessive and, as it emerges in a controlled manner, is not considered significant.

Adequacy of Toe Drainage System

33. In general, it appears that the toe drain is effective in reducing excess hydrostatic pressures in the upper pervious foundation strata and in providing an outlet for controlled emergence of seepage beneath the dam. It is believed therefore that the drain should receive whatever maintenance is necessary to insure its continued effectiveness. In particular, every effort should be made to prevent backflow of surface water into the toe drain which could cause clogging and eventually reduce the efficiency of the drain. The durface drainage ditches constructed for this purpose should continue to receive adequate maintenance. However, even with the ditches in operating condition it is possible for surface water to submerge the toe drainage system during high river stages downstream from the dam. It is possible that such water may in time have a deleterious effect on the performance of the drain. This can be prevented by constructing a small impervious dike having a crown at about el 350 and with a controlled outlet across the old river channel downstream from the outlet of the French drain, and by similar dikes across ditches "A" and "C," see fig. 8. As far as can be ascertained from available data, the efficiency of the drain has not changed since its construction. However, it is considered

desirable to check the future performance of the drain to determine whether submergence by tailwater will reduce the effectiveness of the drain, and whether the above-mentioned dikes are necessary. Therefore, it is considered that piezometric and seepage data should be obtained in the future at periodic intervals.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

34. The conclusions listed below are believed warranted based on the information obtained from this study.

35. The piezometers along the downstream toe of the dam appear to be measuring accurately the hydrostatic pressures in the foundation at the downstream toe of the dam. The computed average gradients from the deep sands to ground surface and from the bottom of the fill in the old river channel to ground surface have never exceeded 0.38 and 0.06, respectively, although the reservoir has reached a stage of 399. It is believed that these gradients will not exceed 0.45 and 0.07, respectively, with the reservoir at the maximum stage (el 410). There is no danger of the foundation sands piping into the fill in the old river channel, because the average gradient from the tips of piezometers immediately below the channel filling to the bottom of channel filling has never exceeded about 0.36, and probably will not exceed 0.42. Furthermore, the channel filling is relatively impervious. The top stratum in the vicinity of sta 13+05B is very thin; however, available piezometric data indicate that little to no excess head will develop immediately beneath the top stratum with a reservoir stage of 410. The foundation downstream of the embankment is considered safe against uplift or blow-out. The fact that the dam has withstood reservoir stages within 85 per cent of the maximum stage, with no noticeable seepage or piping, it is believed to be safe with respect to piping with the reservoir pool at the maximum stage of el 410.

36. Based on piezometric data at sta 15+05B it appears that seepage through the dam passes into the riprap on the downstream face of the dam and thence into the toe drainage system. The piezometers at sta 15+05B are not so located that the effective source of seepage

entry or exit can be determined. Furthermore, readings of these piezometers appear to be affected by rainfall and other factors and are considered to be of questionable value. Future reading of these piezometers does not appear warranted.

37. The Foxboro cells proved to be the most satisfactory of the three types of hydrostatic pressure cells. All six Foxboro cells originally installed are functioning, although it is believed that cells 7 and 10 are no longer functioning properly. Three of the 12 Goldbeck cells are still operating, but none of the 51 Wilson cells is operating. The cells still functioning are generally located in relatively impervious materials and do not warrant continued observations.

Recommendations

38. It is recommended that:

a. Readings of all pressure cells and those piezometers in the embankment and foundation at sta 15+05B be discontinued.

b. Readings be continued for all other piezometers along the downstream toe of the dam to check on the continued effectiveness of the toe drain. Piezometers should be read at 10-ft intervals of rising reservoir stages above conservation pool stage of 355, at the crest, and for 10-ft intervals of falling reservoir stage down to conservation pool level.

c Valves on the piezometer riser pipes be checked periodically to insure that they do not leak.

d. Seepage from the French drain be measured when the reservoir crests appreciably above the conservation pool. The elevation of the water in the area inclosed by the sand bag dikes should be determined at the same time.

e. Maintenance of the surface drainage ditches along the downstream toe of the dam be continued to prevent backflow of surface water into the toe drain.